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π-नेटवर्क में शून्य फेज तकनीक द्वारा क्वार्टज क्रिस्टल इकाई के पैरामीटरों का मापन

भाग 1 π-नेटवर्क में शून्य फेज तकनीक द्वारा क्वार्टज क्रिस्टल इकाइयों की अनुनाद आवृत्ति तथा अनुनाद प्रतिरोध के मापन की मूल पद्धति

(पहला पुनरीक्षण)

Indian Standard

MEASUREMENT OF QUARTZ CRYSTAL UNIT PARAMETERS BY ZERO PHASE TECHNIQUE IN A π-NETWORK

PART 1 BASIC METHOD FOR THE MEASUREMENT OF RESONANCE FREQUENCY AND RESONANCE RESISTANCE OF QUARTZ CRYSTAL UNITS BY ZERO PHASE TECHNIQUE IN A π-NETWORK

(First Revision)

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NEW DELHI 110002

December 2001

Price Group 10

Piezoelectric Devices for Frequency Control and Selection Sectional Committee, LTD 12

NATIONAL FOREWORD

This Indian Standard (Part 1) (First Revision) which is identical with IEC 60444-1 (1986) 'Measurement of quartz crystal unit parameters by zero phase technique in a π-network — Part 1 Basic method for the measurement of resonance frequency and resonance resistance of quartz crystal units by zero phase technique in a π-network' including Amendment 1 (1999), issued by the International Electrotechnical Commission (IEC), was adopted by the Bureau of Indian Standards on the recommendation of the Piezoelectric Devices for Frequency Control and Selection Sectional Committee and approval of the Electronics and Telecommunication Division Council

This standard specifies method of measurement of resonance frequency and resonance resistance of quartz crystal units and describes a suitable measuring network for use over the frequency range 1 MHz to 200 MHz

This standard was first published in 1974 and was based on IEC 60444-1 (1973) However, IEC 60444-1 has since been revised in 1986 In view of the technological advances at the International level, this standard is being revised to align it with Part 1 of IEC 60444 series The other parts of IEC 60444 series are given below which may be considered for adoption as Indian Standards in due course of time

Part 2 Phase offset method for measurement of motional capacitance of quartz crystal units

Part 3 Basic method for the measurement of two-terminal parameters of quartz crystal units up to 200 MHz by phase technique in a π-network with compensation of the parallel capacitance C_0

Part 4 Method for the measurement of the load resonance frequency f_L, load resonance resistance R_L and the calculation of other derived values of quartz crystal units up to 30 MHz

Part 5 Methods for the determination of equivalent electrical parameters using automatic network analyser techniques and error correction

Part 6 Measurement of drive level dependence (DLD)

The text of the IEC has been approved as suitable for publication as Indian Standard without deviations Certain conventions are, however, not identical to those used in Indian Standards Attention is particularly drawn to the following

a) Wherever the words 'International Standard' appear referring to this standard they should be read as 'Indian Standard'

b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point ( ) as the decimal marker

Amendment 1 to the above International Standard has been printed at the end

Only the English language text of the International Standard has been retained while adopting it in this Indian Standard

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Indian Standard

MEASUREMENT OF QUARTZ CRYSTAL UNIT PARAMETERS BY ZERO PHASE TECHNIQUE IN A π-NETWORK

PART 1 BASIC METHOD FOR THE MEASUREMENT OF RESONANCE FREQUENCY AND RESONANCE RESISTANCE OF QUARTZ CRYSTAL UNITS BY ZERO PHASE TECHNIQUE IN A π-NETWORK

(First Revision)

1. Scope

This standard specifies a simple method of measurement of resonance frequency and resonance resistance of quartz crystal units and describes a suitable measuring network.

The measuring method and the network are suitable for use over the frequency range 1 MHz to 200 MHz with a fractional frequency accuracy of the order of 10^{-6} with a reproducibility of 10^{-6} to 10^{-8} depending on the type of crystal unit being measured, and an accuracy of the measurement of resonance resistance of ±2% to ±5% depending on the accuracy of the voltage measurement.

However, above approximately 100 MHz the use of this measuring method is limited by the effects of the shunt capacitance C_0 of the crystal unit under test. To enable the measuring method to be used under these conditions, the use of some method of C_0 compensation is advisable.

A method of C_0 compensation will be issued in IEC Publication 444-3 as an IEC report.

Note — The modifications to the measuring system and network contained in this standard have been introduced to ensure that the claims contained within it are achievable. They do not, however, invalidate the network produced according to the first edition. These networks are still acceptable as an international standard method of measurement of resonance frequency f_r and resonance resistance R_r.
If the reference resistors described in the standard are slightly modified to allow insertion into networks manufactured according to the first edition of Publication 444 then the problem of obtaining satisfactory reference resistors is solved.

2. Definition of resonance frequency

The crystal unit is a 3-terminal network with a complex transfer admittance $Y_{12} = G_{12} + jB_{12}$, as defined in Sub-clause A1.1 of Appendix A.

The enclosure is considered as the common terminal.

For glass enclosures, the third terminal is defined in Clause 3.

The resonance frequency is defined as the lower of the two frequencies of the crystal unit alone under specified conditions at which B_{12} is zero.

At this frequency, the resonance resistance is $1/G_{12} = R_r$.

3. Reference plane and shielding box

Because of lead inductance of the crystal unit it is necessary to specify a reference plane at which the measurements are to be made. This plane is located at a distance of 2 mm from the place where the pins or leads emerge from the crystal unit, unless otherwise specified. The third terminal for glass enclosures is a metal shielding box with internal dimensions 27 mm in height and the base plane of 40 mm x 40 mm (base plane = reference plane) and closed at the top. The crystal unit is to be located at the centre of the base plane of the shielding box.

4. Principle of measurement

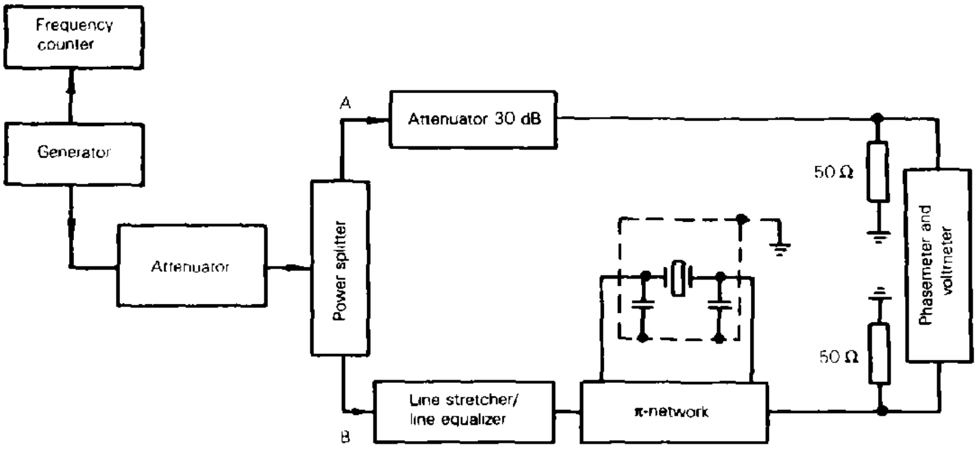
The measurement is reduced to a 2-terminal impedance measurement by inserting the crystal unit in a π-network (see Figure 1).

The phase of the crystal transfer admittance is indicated on a phasemeter connected across the π-network. The frequency giving zero phase reading is measured.

Zero phase is calibrated by inserting a reference resistor in the π-network. The value of the resonance resistance can be calculated from the voltage readings on channels A and B.

5. Measuring circuit

The measuring circuit consists basically of a π-network connected with coaxial cables to the associated equipment (see Figure 1).



Notes 1 — The 30 dB attenuator in channel A may be desirable with certain phasemeters and voltmeters

2 — The line stretcher of constant impedance in channel B may be desirable for ease of equalizing the electrical length of the connecting cables. (A "line stretcher" with variable length is a phase equalizing device of constant impedance.)

3. — When using some generators it may be advisable to use a filter to reduce the harmonic distortion to the level specified in Sub-clause 5.3.1.1

FIGURE 1

The fact is emphasized that the construction of the π-network determines the accuracy of the set-up, whereas the associated equipment can be extended, if necessary, to produce a very sophisticated set-up. For this reason, only the essential elements of the associated equipment are specified (see Sub-clause 5.3).

5.1 *The π-network*

5.1.1 *Electrical specification*

5.1.1.1 *Circuit diagram*

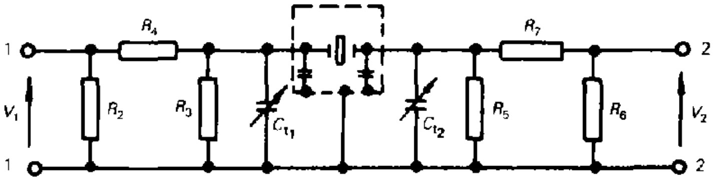


FIGURE 2

$R_2 = R_6 = 159\ \Omega$ (disk type)

$R_3 = R_5 = 14.2\ \Omega$ (disk type)

$R_4 = R_7 = 66.2\ \Omega$ (rod type)

Tolerance ±1%

$C_{t_1} = C_{t_2} = 0.5$ pF to 5 pF (air trimmer)

Note — The function of the input and output pads is twofold.
a) to match the crystal impedance to the associated equipment;
b) to attenuate reflections from the associated equipment.

5.1.1.2 The frequency range shall be 1 MHz to 200 MHz.

5.1.1.3 The logarithmic ratio of the respective voltages at the B-channel with and without the shorting blank inserted in the π-network is termed the "cross-talk attenuation" of the π-network test set-up. The cross-talk attenuation a_c (in decibels) is given by the expression:

$$a_c = 20 \log \frac{V_{Bs}}{V_{Bo}},$$

where V_{Bs} is the voltage at the B-channel with the shorting blank inserted into the π-network and V_{Bo} is the voltage at the B-channel with the shorting blank removed from the π-network. Measured at a frequency of 100 MHz in the measuring circuit according to Figure 1, page 4, the cross-talk attenuation shall be $\geqslant 60$ dB.

5.1.1.4 At all frequencies between 1 MHz and 200 MHz the phase measured at 75 Ω shall not deviate by more than ±0.2° from the phase measured at 25 Ω in the measuring circuit according to Figure 1 (see Sub-clause 6.1).

At a frequency of 200 MHz, the phase over the resistance range 15 Ω to 100 Ω shall not deviate by more than ±0.5° from the phase measured at 25 Ω in the measuring circuit according to Figure 1 (see Figure 3, page 6, and Sub-clause 6.1).

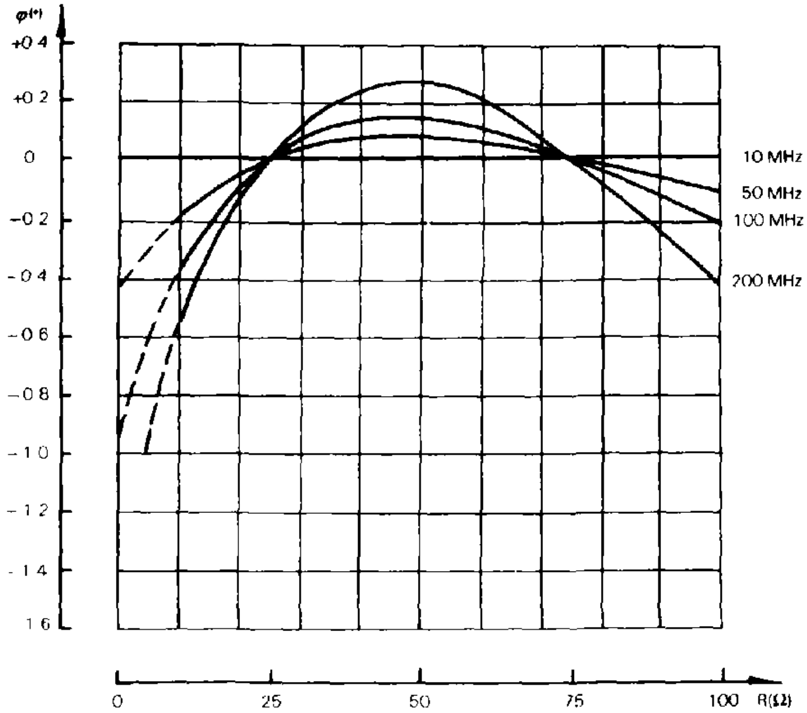


FIG. 3. – Plot showing the phase change from the value at 25 Ω versus reference resistor values from 0 to 100 Ω at 10 MHz, 50 MHz, 100 MHz and 200 MHz. Measuring circuit according to Figure 1, page 4.

5.1.1.5 At all levels of drive between 5 μW and 5 mW the phase measured at 25 Ω shall not deviate by more than ±0.5° over the frequency range 1 MHz to 200 MHz from the phase measured at 0.5 mW in the measuring circuit according to Figure 1.

5.1.1.6 At all frequencies between 1 MHz and 200 MHz the resistance of the 25 Ω reference resistor shall not deviate by more than 2% from the value measured at 1 MHz in the measuring circuit according to Figure 1.

5.1.1.7 At a frequency of 200 MHz, the reflection coefficient measured with the shorting blank having the dimensions of Sub-clause 5.2.2 shall be less than 5% within the reference temperature range −55 °C to +105 °C. The output and input shall be terminated within 50 Ω.

5.1.1.8 Measured with the shorting metal blank of Sub-clause 5.2.2 in the π-network, the insertion attenuation over the specified frequency range shall be 29.6 ± 0.3 dB.

5.1.1.9 The stray capacitance between contact plates shall be smaller than 0.05 pF.

5.1.1.10 With the 25 Ω reference resistor of Sub-clause 5.2.1 in the π-network set-up as Figure 1, page 4, the phase is measured over the temperature range −55 °C to +105 °C at a frequency of 200 MHz. The permissible difference is ± 0.2° with reference to the value at +25 °C.

5.1.1.11 The resistance between the contact plates and the body of the terminated π-network shall be 12.5 Ω. The tolerance is defined by the tolerances of R_2 to R_7 (Figure 2, page 5).

5.1.2 *Mechanical specification*

Typical π-networks which meet the requirements of Sub-clause 5.1.1 consist of the following parts (see Figures A9 to A13, pages 18 to 21).

a) Two resistive attenuators (14.8 dB each) in a metal body, consisting of resistors R_2 to R_7 (see Figure 2).

b) Two coaxial connectors (50 Ω) with sufficiently low contact resistance.

c) Two contact plates against which the crystal terminals are pressed. The contacts with the crystal terminals shall be made at the top edges of contact plates, which serve to define the reference plane.

d) Two spring-loaded plastic blocks.

e) Plastic spacer to determine the location of the reference plane.

f) Dielectric.

g) Two high-frequency precision air trimmers 0.5 pF to 5 pF Ct_1 and Ct_2 (see Figure 2).

5.2 *Accessories of the π-network*

5.2.1 *Reference resistors*

The resistors used for calibration are as shown in Figure 4, page 8.

Resistance values for initial calibration are 15 Ω, 25 Ω, 50 Ω, 75 Ω and 100 Ω. D.C resistance tolerance: ± 1%.

5.2.2 *Shorting blank*

The shorting blank is a metal plate with dimensions 12 mm × 10 mm × 1 mm (see Figure 4).

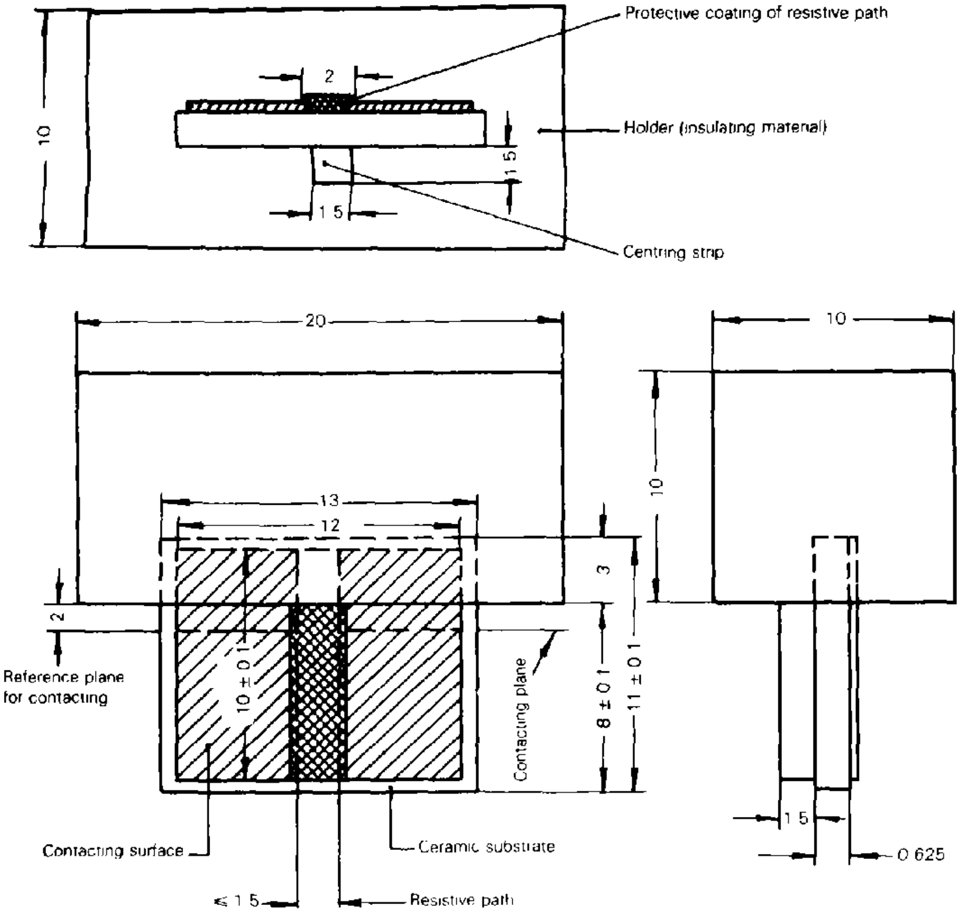
5.3 *Associated equipment*

5.3.1 *Generator*

5.3.1.1 At both sides of the frequency for which the generator is adjusted and within 10% of that frequency, the total output power, apart from that at the adjusted frequency, shall be at least 60 dB below the main output.

The level of spurious oscillations and harmonics from the generator shall be sufficiently low for the accuracy of the phasemeter not to be affected (typical value: −40 dB). The frequency resolution and stability of the generator shall be adequate to enable measurements to be carried out on the highest Q crystal under consideration (typical value better than $1 \cdot 10^{-7}$).

5.3.1.2 The phase noise is measured at resonance frequency in the set-up of Figure 1 with a high Q crystal ($Q > 500\,000$) in the π-network. The indicated phase jitter shall be less than 0.2°.



Notes 1 – All dimensions are in millimetres and critical dimensions are given with tolerances.

2. – The shorting blank and the reference resistors are identical in respect of dimensions and locations of the reference and contacting planes

FIG. 4. – Reference resistors and shorting blank.

5.3.1.3 The maximum available output power level shall be at least nominal crystal drive level +24 dB.

5.3.1.4 Source impedance is 50 Ω.

5.3.2 *Variable attenuator (50 Ω)*

The variable attenuator may be incorporated in the generator. Required for drive level adjustment only.

5.3.3 *Power splitter*

A power splitter may be incorporated in the π-network.

Two types of power splitter may be used in a π-network (see Figures 5a and 5b). With that illustrated in Figure 5a the incident wave is measured and with that in Figure 5b both incident and reflected waves are measured.

In practice Figure 5a and Figure 5b give a combination of incident as well as reflected waves; this has little effect on the results of measurements in the π-network.

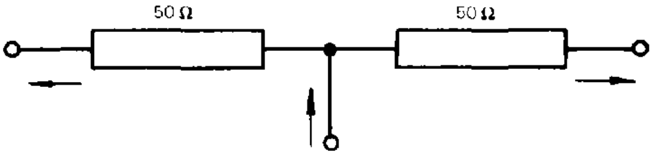


FIGURE 5a

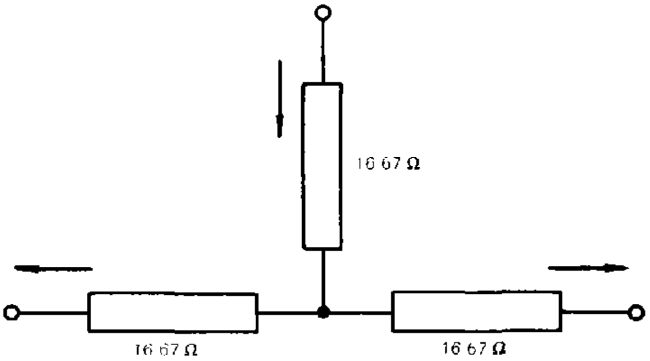


FIGURE 5b

5.3.4 *Phasemeter and voltmeter*

The phasemeter serves as an indicator. From the voltmeter reading the resonance resistance can be deduced.

Requirements are described in Sub-clauses 5.3.4.1 to 5.3.4.4.

5.3.4.1 Phase error at zero reading as a function of time (zero drift) and as a function of voltage change by a factor of 5 measured at channel B shall be less than 0.2°.

Note. — Precautions should be taken that harmonics do not affect the accuracy of the phase reading.

5.3.4.2 The sensitivity on channel B shall be at least crystal drive level −25 dB.

5.3.4.3 The reflection coefficients at A and B-channel terminals shall be less than 2%. Impedance is 50 Ω.

5.3.4.4 The ratio of voltages on channels A and B shall be measured with a precision of 2%.

5.3.5 *Cables*

5.3.5.1 Double-shielded cables or preferably full metal coaxial lines (50 Ω) capable of withstanding the temperature range −55 °C to +105 °C shall be used.

5.3.5.2 The reflection coefficients at the cable terminals shall be less than 5%.

5.3.5.3 It is preferable but not essential to choose the length of the cables connecting the output of the power splitter to the input of the π-network so that, with reference resistor of 25 Ω inserted in the π-network, the phase shift between channels A and B at all frequencies within the range of 1 MHz to 200 MHz is not more than ± 0.5°. For ease of alignment use can be made of a line stretcher of variable length of constant impedance.

5.3.6 *Frequency meter*

The accuracy and stability of the frequency meter shall be better than $1 \cdot 10^{-8}$

6. Method of measurement

6.1 *Initial calibration of the π-network*

6.1.1 Insert the shorting blank in the π-network.

6.1.2 Adjust the signal generator to a frequency of 100 MHz and adjust the output level so that the voltage reading V_{Bs} of the B-channel is 100 mV.

6.1.3 Remove the shorting blank.

6.1.4 Record the voltage reading V_{Bo} of the B-channel.

6.1.5 Calculate:

$$a_c = 20 \log \frac{V_{Bs}}{V_{Bo}}$$

a_c shall be ⩾60 dB.

6.1.6 Adjust the trimming capacitors C_{t_1} and C_{t_2} of the π-network to the maximum value.

6.1.7 Insert the 25 Ω reference resistor in the π-network.

6.1.8 Adjust the signal generator to a frequency of 200 MHz and adjust the output level so that the level of drive is 0.5 mW.

6.1.9 Adjust the phasemeter to zero reading.

6.1.10 Replace the 25 Ω reference resistor by the 75 Ω reference resistor.

6.1.11 Adjust the trimming capacitors simultaneously until the phasemeter reading is zero.

6.1.12 Repeat steps 7 to 11 until the difference between the zero phase positions at steps 9 and 11 is $\varphi \leqslant \pm 0.1°$.

6.1.13 Ensure that the phase complies with the requirements described in Sub-clause 5.1.1.4.

6.1.14 Adjust the signal generator to a frequency of 1 MHz.

6.1.15 Insert the 25 Ω reference resistor in the π-network.

6.1.16 Adjust the phase meter to zero reading.

6.1.17 Adjust the signal generator to a frequency of 150 MHz.

6.1.18 Adjust the line stretcher/line equalizer so that the phase reading is within ± 0.1° of that obtained at step 16.

Note — The procedures in Sub-clauses 6.1.14 to 6.1.18 are preferable but not essential. However, if they are carried out, then the network will have nearly constant phase over a wide frequency range (see Figure A8, page 17), and frequent recalibration as set out in Sub-clauses 6.2.2.1 and 6.2.2.2 may not be necessary.

6.1.19 Ensure that the variation of phase with frequency complies with the requirement described in Sub-clause 5.1.1.4.

6.1.20 Ensure that the variation of phase with drive level complies with the requirement described in Sub-clause 5.1.1.5.

6.1.21 Ensure that the resistance deviation required by Sub-clause 5.1.1.6 is satisfied.

6.1.22 To check the system, it is good practice to make π-network measurements in both directions, i.e. by reversing input and output connections.

6.2 *Frequency and resistance measurement*

6.2.1 *Initial calibration*

6.2.1.1 Insert the 25 Ω reference resistor in the π-network.

6.2.1.2 Adjust the signal generator to nominal frequency ± 0.1 % and adjust the output level so that the level of drive is 0.5 mW, unless otherwise specified.

Note — Further explanation is given in Sub-clause A2.1 of Appendix A

6.2.1.3 Record the A and B channel voltage readings, V_{An} and V_{Bn} respectively.

Calculate:

$$K_n = \frac{V_{Bn}}{V_{An}}$$

6.2.2 *Measurement*

6.2.2.1 Insert the 25 Ω reference resistor in the π-network.

6.2.2.2 Adjust the phasemeter to zero phase reading.

6.2.2.3 Replace the reference resistor by the crystal unit to be measured and earth the metal enclosure or shield, whichever is applicable.

6.2.2.4 Adjust the frequency for zero phase reading.

6.2.2.5 Read frequency.

6.2.2.6 Take A and B channel voltage readings V_{Ac} and V_{Bc} respectively.

6.2.2.7 The resonance resistance can be calculated from the formula:

$$R_r = (2K_n \frac{V_{Ac}}{V_{Bc}} - 1)\ 25\ \Omega.$$

APPENDIX A

ADDITIONAL INFORMATION ON ACCURACY

A1. Analysis of the measurement

A1.1 A piezoelectric quartz crystal unit can be considered as a 3-terminal network.

In general, a 3-terminal network (see Figure A1) can be described by the admittance matrix:

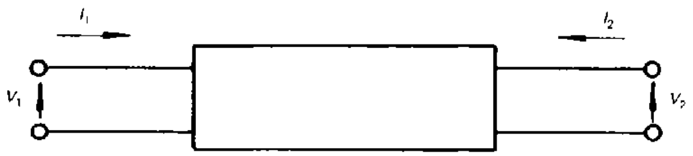


FIGURE A1

$I_1 = Y_{11}V_1 + Y_{12}V_2$

$I_2 = Y_{21}V_1 + Y_{22}V_2$

$Y_{12} = Y_{21}$ for a reciprocal network.

If the network is a π (see Figure A2), the matrix is.

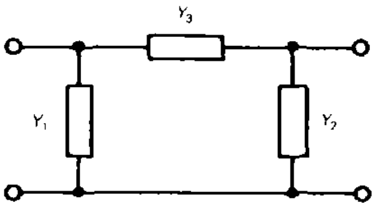


FIGURE A2

$Y_{11} = Y_1 + Y_3$

$Y_{22} = Y_2 + Y_3$

$Y_{12} = Y_{21} = -Y_3$ transfer admittance.

Applied to a crystal unit, the network is:

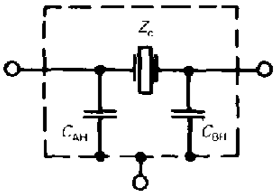


FIGURE A3

$Y_1 = j\omega\, C_{AH}$

$Y_2 = j\omega\, C_{BH}$

$Y_3 = 1/Z_c$

Z_c = crystal impedance if $C_{AH} = C_{BH} = 0$.

A1.2 *π-network*

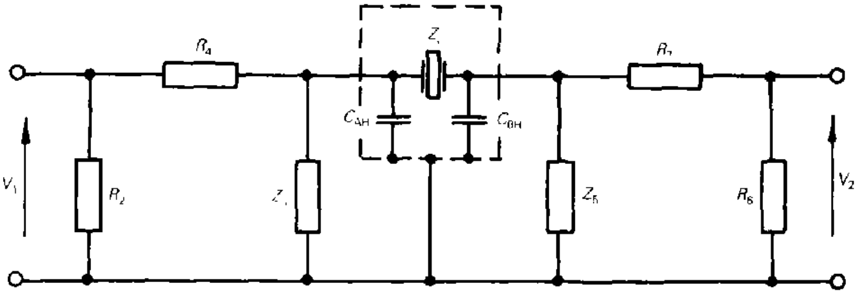


FIGURE A4

The voltage transfer is

$$\frac{V_2}{V_1} = \frac{R_6}{R_6 + R_7} \cdot \frac{1}{R_4 \cdot A_2 \cdot A_4} \cdot \frac{1}{Z_c + \dfrac{1}{A_2} + \dfrac{1}{A_4}}$$

in which.

$$A_2 = \frac{1}{Z_3} + \frac{1}{R_4} + j\omega\, C_{AH} \text{ and } A_4 = \frac{1}{Z_5} + \frac{1}{R_6 + R_7} + j\omega\, C_{BH}.$$

Apparently the crystal unit is loaded with a series impedance.

$$\frac{1}{A_2} + \frac{1}{A_4} = Z_s.$$

For the purpose of this standard, all the stray reactances have been considered to be lumped in impedances Z_3 and Z_5.

A2. *Accuracy of the measurement*

Although the set-up has been designed to give a very good accuracy, there remain three sources of minor errors:

A2.1 *Variation of drive level*

In general, the resonance frequency and resonance resistance of a crystal unit are dependent on the level of drive. The magnitude of this effect is determined by the crystal unit under test.

However, the design of the π-network is such that a change of resonance resistance does not seriously affect the drive level (see Figure A5).

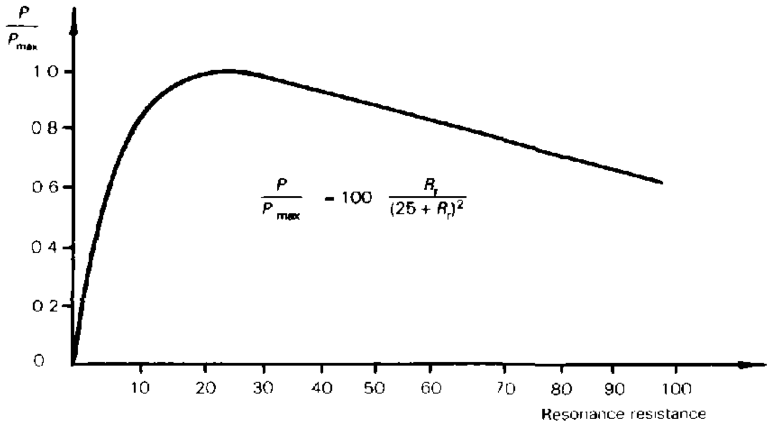


FIGURE A5

For example, a change of resonance resistance from 9.5 Ω to 65.5 Ω results in a change of power level of 20%. In most cases, this is acceptable.

For crystals with a very high or very low resonance resistance, the drive level may be adjusted according to Figure 10, if required

A2.2 *Phase shifts*

In the neighbourhood of resonance frequency, the phase of:

$$Z_c + Z_s \text{ is } \varphi = \frac{2\Delta f}{f} \cdot Q_{\text{eff}},$$

φ in radians.

$$\Delta f = f - f_r \text{ and } Q_{\text{eff}} = \frac{1}{2\pi f_r (R_3 + R_5 + R_r) C_1},$$

so:

$$\frac{\Delta f}{f} = \frac{\varphi}{2Q_{\text{eff}}}.$$

For example, for a crystal of 60 MHz and a $Q_{\text{eff}} = 40\,000$, the resulting relative frequency error is 1.10^{-7} for a residual phase error of 0.45°.

A2.2.1 *Phase errors due to a change of R_r*

The phase errors due to a change of R_r can for all practical purposes be eliminated by replacing the crystal unit by a (nearly ideal) reference resistor (see Figure 4, page 8) with a resistance approximately equal to R_r.

A2.2.2 *Phase errors due to crystal enclosure dimensions*

The contacting plates of the π-network enable insertion of various types of crystal enclosures.

The distance between the pins or leads emerging from the crystal unit may vary from 2.4 mm to approximately 40 mm. The phase error between a very small crystal unit and a reference resistor may be considered to be zero The phase errors due to usual larger crystal unit dimensions depend on the distance between the crystal unit leads and the distance between the rod and disk centres of the π-network (see Figure A6). With the present network these errors are almost negligible. For example, for a 100 MHz crystal unit having a resonance resistance of 50 Ω and lead distance of 10.0 mm, the phase error appears to be approximately 1.2°, and for a 200 MHz crystal unit having a resonance resistance of 100 Ω and a lead distance of 6 mm, the phase error appears to be approximately 1.3°

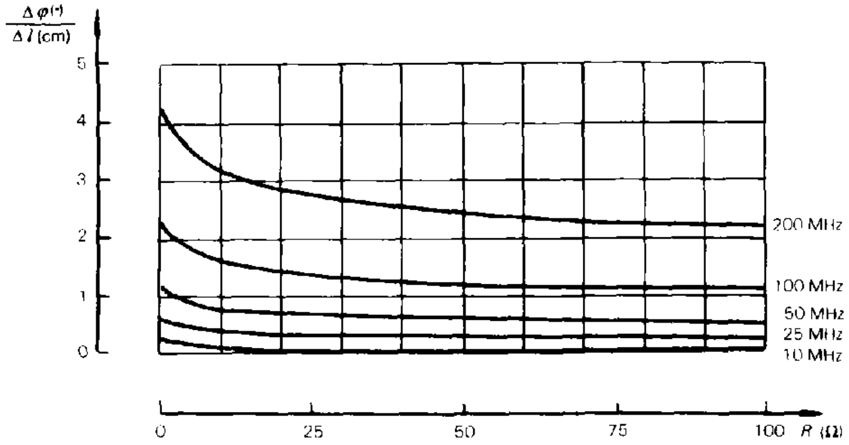


FIGURE A6

A2.3 *Stray holder capacitances*

The influence of the stray holder capacitances C_{AH} and C_{BH} on the measurement of resonance frequency is as follows: the holder capacitances are in parallel with Z_3 and Z_5 (see Figure A4, page 13).

The impedance of the combination Z_3 and C_{AH} is:

$$Z_3' = \frac{Z_3}{1 + Z_3 j\omega C_{AH}} \text{ and similarly } Z_5' = \frac{Z_5}{1 + Z_5 j\omega C_{BH}}.$$

For example, if f_r = 100 MHz, $C_{AH} = C_{BH}$ = 2 pF, C_1 = 0.7 f F and $Z_3 = Z_5$ = 12.5 Ω

then: $Z_3' = Z_5' = 12.5 - 0.19\,j$.

Ignoring the holder capacitances results in a systematic frequency error of.

$$\frac{\Delta f}{f} = 8 \times 10^{-7} \text{ for } Q_{\text{eff}} = 20\,000.$$

Hence, the difference will be the same for all π-networks

A3. Compensation of inductance of R_3 and R_5

In general, the equivalent circuit of a resistor (as Z_3 and Z_5 of Figure A4, page 13) measured at high frequency is (see Figure A7, below):

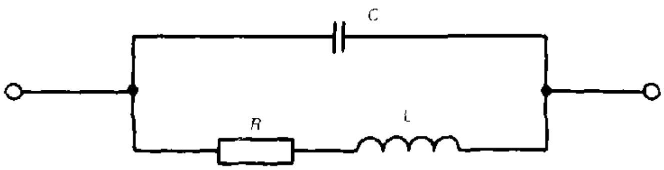


FIGURE A7

The admittance is.

$$A = j\omega C + \frac{1}{R + j\omega L} = \frac{R j\omega C + 1 - \omega^2 LC}{R + j\omega L}$$

A is resistive if $R^2C = (1 - \omega^2 LC)L$.

If $\omega^2 LC \ll 1$, then $R^2 = L/C$.

The condition $\omega^2 LC \ll 1$ may then be written as $\omega L \ll R$. The validity of this relation will be checked at a second frequency.

In the present state of the art, C appears to be approximately 10 pF for a compensated network, $\omega L \ll R$.

With $R = 12.5\ \Omega$, $C = 10$ pF and $R^2 = \dfrac{L}{C}$,

$L = 1.5 \times 10^{-9}$ H.

With $f_c = \dfrac{1}{2\pi\sqrt{LC}}$,

the cut-off frequency f_c is approximately 1 000 MHz With the cos of phase angle $= 1 - 2\left(\dfrac{f}{f_c}\right)^2$ the phase linearity will be better than ±0.25° up to 250 MHz. Hence compensation within ±0.25° is possible up to 200 MHz (see Figure A8, page 17).

A4. *Measurement error of resonance resistance*

The measurement error of resonance resistance is:

$$\Delta R_r = \left(\frac{\Delta V_{Bs}}{V_{Bs}} + \frac{\Delta V_{Ac}}{V_{Ac}} - \frac{\Delta V_{As}}{V_{As}} - \frac{\Delta V_{Bc}}{V_{Bc}} \right) \cdot \frac{V_{Ac}}{V_{As}} \cdot \frac{V_{Bs}}{V_{Bc}} \cdot 25,$$

where

ΔV_{Ac} = error in V_{Ac}
ΔV_{As} = error in V_{As}
ΔV_{Bc} = error in V_{Bc}
ΔV_{Bs} = error in V_{Bs}

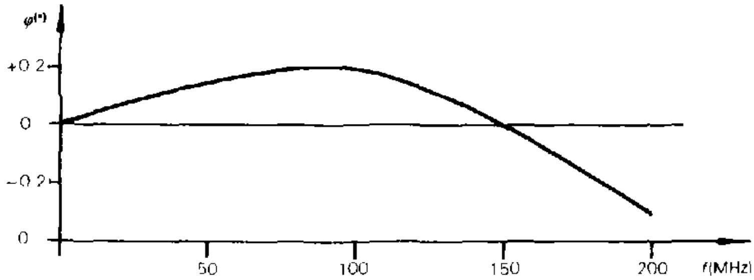


FIG. A8. — A typical phase/frequency variation of an adjusted π-network with a 25 Ω reference resistor

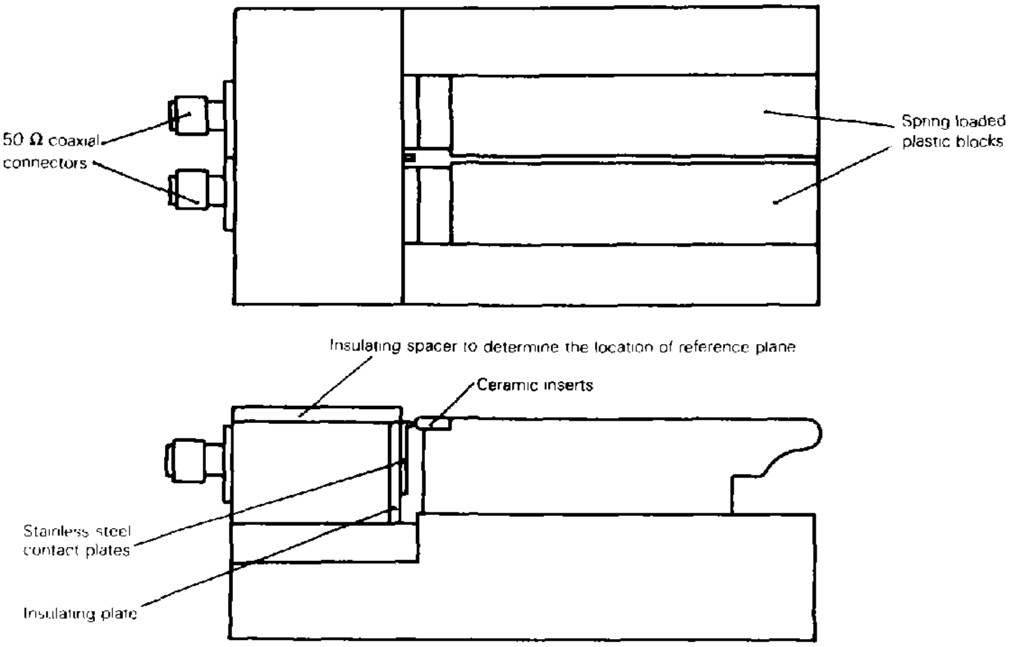

50 Ω coaxial connectors
Spring loaded plastic blocks
Insulating spacer to determine the location of reference plane
Ceramic inserts
Stainless steel contact plates
Insulating plate

FIG A9 — Typical π-network

Dimensions in millimetres

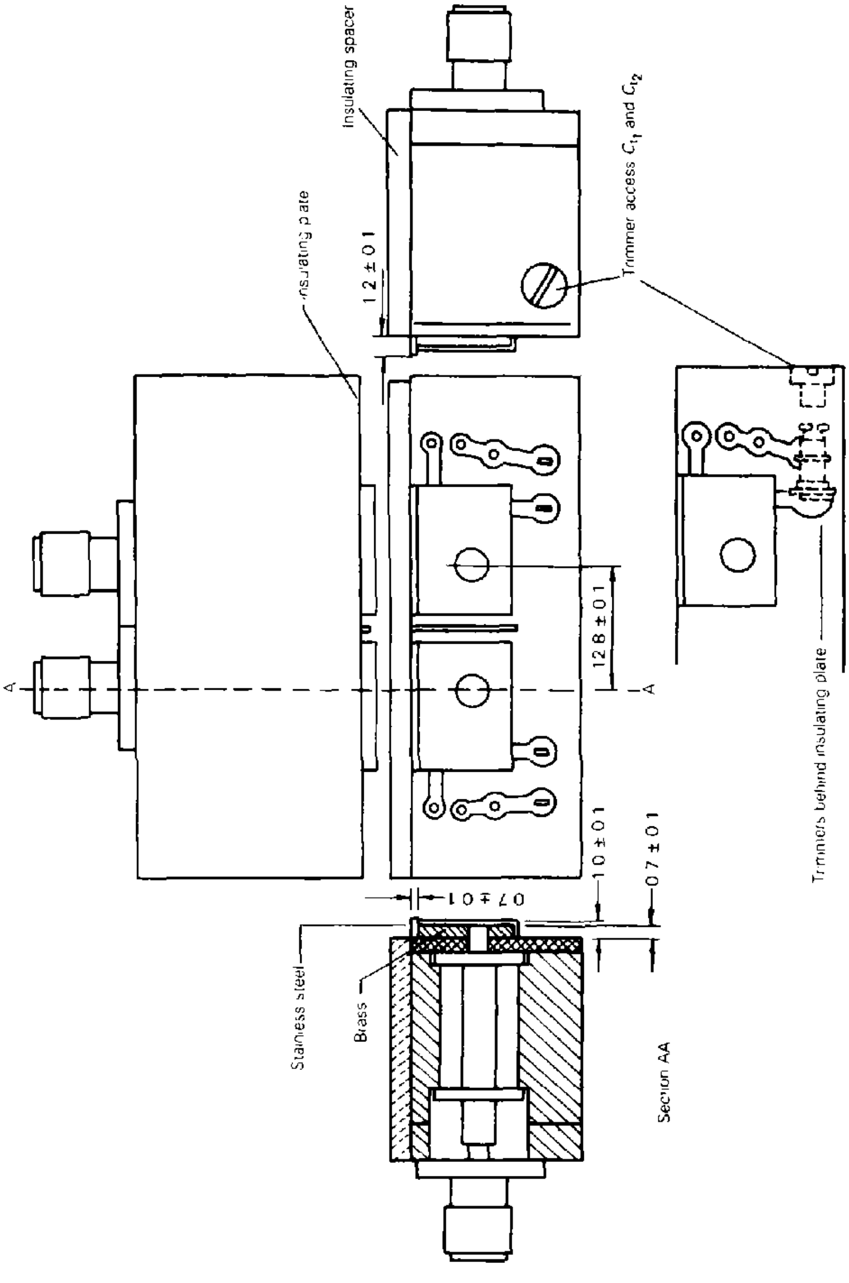
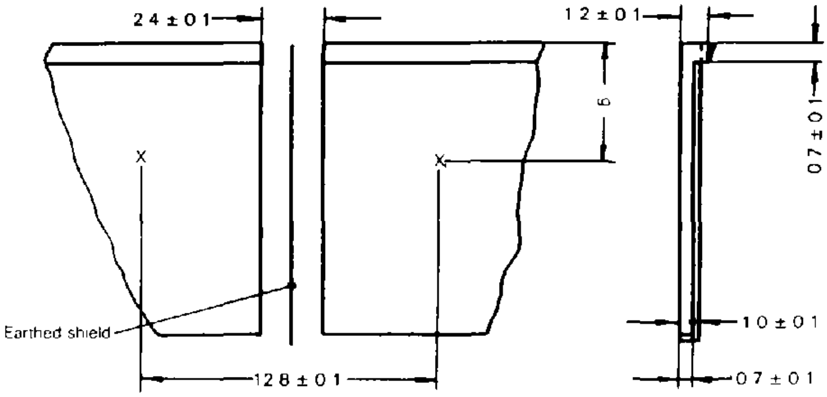
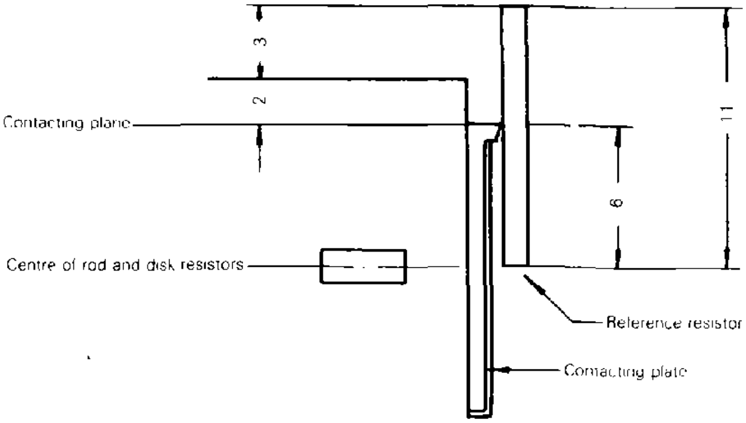


FIG A10. — Detail of network assembly.



Dimensions in millimetres

FIG A11. — Dimensions of contacting plates and earthed shield, x indicates position of rod and disk centres of π-network



Dimensions in millimetres

FIG A12. — Position of the reference resistor with respect to the network contacting plates.

Dimensions in millimetres

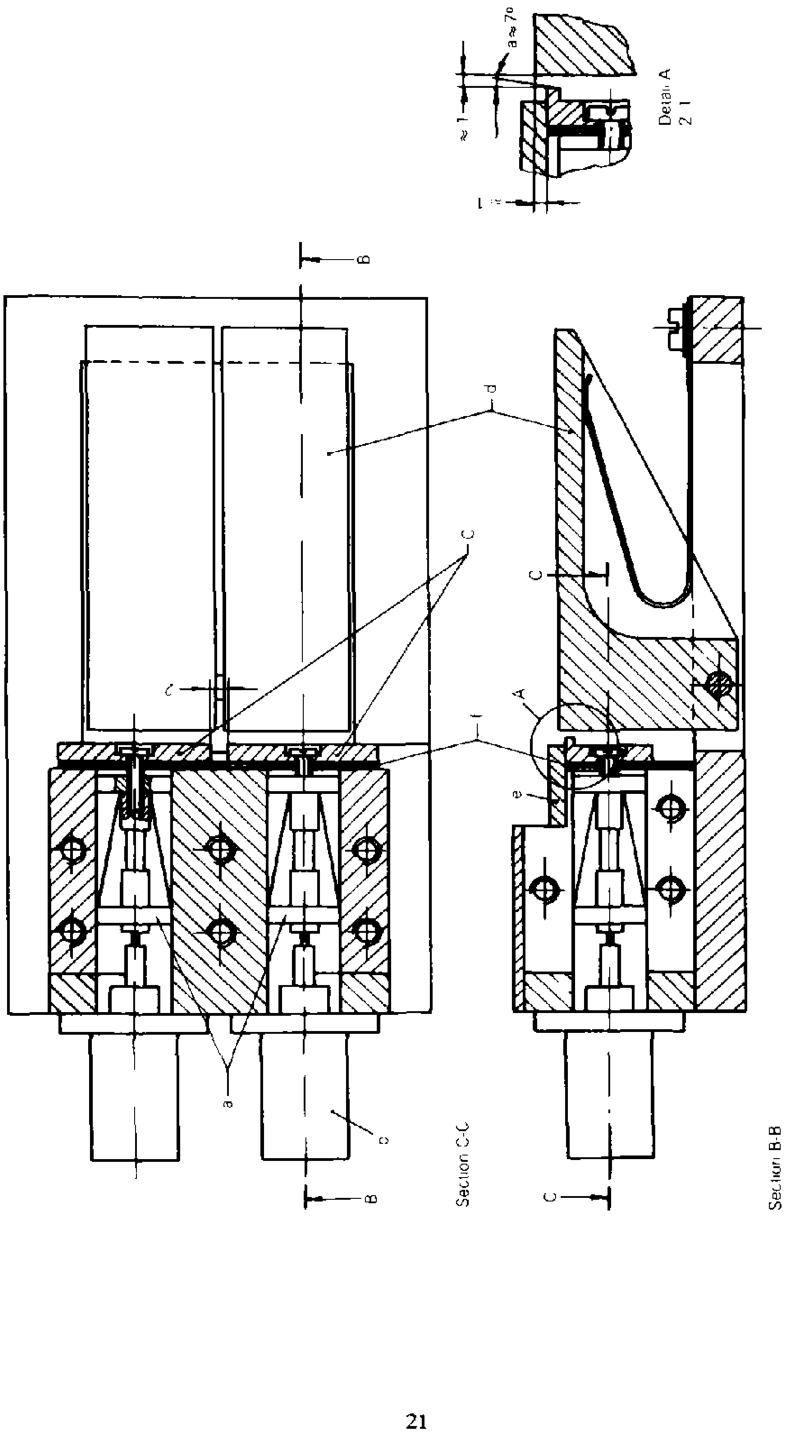


FIG. A13. — Other design of a π-network.

AMENDMENT NO. 1

Page 1

CONTENTS

Add the title of annex B as follows:

Annex B – Updating of some formulae of appendix A

Page 21

Add, after appendix A, the new annex B as follows:

Annex B
(normative)

Updating of some formulae of appendix A

B.1 Purposes

In this annex some formulae of the appendix A are updated, taking into account the modified calibration procedure of the π-network with a reference resistor R_n = 25 Ω instead of a short.

The formula relating R_r to the measured voltages is derived for arbitrary values of the reference resistor R_n. The error of R_n is taken into account in the error analysis for R_r.

The formula for current and drive level of the crystal in the π-network is given. The phase slope of the crystal inserted in the π-network is derived and the formula for Q_{eff} is corrected.

B.2 The π-network terminated by Z = 50 Ω (with power splitter according to figure 5a)

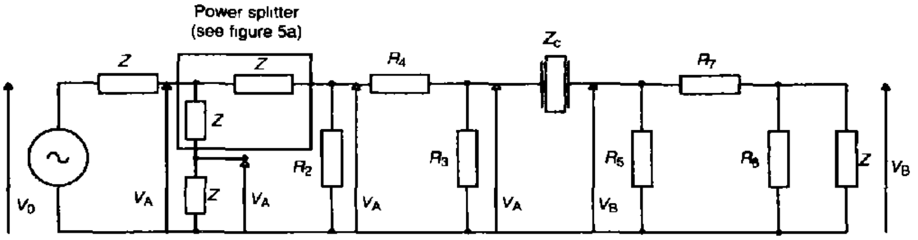


Figure B.1 – Terminated π-network

B.3 Voltage transfer factor of the terminated π-network

In the following an elementary derivation of the voltage transfer factor is presented to provide a more comprehensive formula

Let $R_6' = R_6 \,||\, Z = \left(\frac{1}{R_6} + \frac{1}{Z} \right)^{-1}$

Then $$\frac{V_B}{V_B'} = \frac{R_6'}{R_6' + R_7} = k_\pi = 0{,}3649 \qquad \text{(B 1)}$$

Define $R_5' = R_5 \,||\, \left(R_6' + R_7 \right) = \left(\frac{1}{R_5} + \frac{1}{R_6' + R_7} \right)^{-1} = R_{T2} = 12{,}5\ \Omega$

where R_{T2} is the termination resistance at the output of the π-network as seen by the crystal.

Then $$\frac{V_B'}{V_A'} = \frac{R_5'}{R_5' + Z_c} \qquad \text{(B 2)}$$

Define $R_3' = R_3 \,||\, \left(R_5' + Z_c \right) = \left(\frac{1}{R_3} + \frac{1}{R_5' + Z_c} \right)^{-1}$

Then $$\frac{V_A'}{V_A''} = \frac{R_3'}{R_3' + R_4} \qquad \text{(B 3)}$$

Define $R_2' = R_2 \,||\, \left(R_3' + R_4\right) = \left(\frac{1}{R_2} + \frac{1}{R_3' + R_4}\right)^{-1}$

Then, for a power splitter according to figure 5a and disregarding the cables.

$$\frac{V_A''}{V_A'} = \frac{R_2'}{R_2' + Z} \qquad \text{(B.4)}$$

and $\frac{V_A'}{V_A} = \frac{2Z}{Z} = 2$ (B.5)

The voltage transfer factor $V_B \,/\, V_A$ is obtained by multiplying formulae (B.1) × (B.2) × (B.3) × (B.4) × (B.5):

$$\frac{V_B}{V_A} = \frac{V_B}{V_B'} \times \frac{V_B'}{V_A'''} \times \frac{V_A'''}{V_A''} \times \frac{V_A''}{V_A'} \times \frac{V_A'}{V_A}$$

After some substitutions and rearrangements it can be shown that

$$\frac{V_B}{V_A} = \frac{R_2 R_{T1}\, 2\, Z\, R_{T2} R_6}{\left(Z(R_2 + R_4) + R_2 R_4\right) \times \left(Z(R_6 + R_7) + R_6 R_7\right)} \times \frac{1}{Z_c + R_{T1} + R_{T2}} \qquad \text{(B.6)}$$

where

$$R_{T1} = \left(\frac{1}{R_3} + \frac{1}{R_4 + \left(\frac{1}{R_2} + \frac{1}{Z} \right)^{-1}} \right)^{-1} = 12{,}5\ \Omega$$

and

$$R_{T2} = \left(\frac{1}{R_5} + \frac{1}{R_7 + \left(\frac{1}{R_6} + \frac{1}{Z} \right)^{-1}} \right)^{-1} = 12{,}5\ \Omega$$

V_B/V_A is symmetric with respect to the input and the output of the π-network and splits into a factor which depends only on Z and the resistance values of the π-network and a factor which depends on the crystal impedance Z_c loaded by the termination impedances of the π-network.

$$\frac{V_B}{V_A} = K(R_2 \ldots R_7, Z) \times \frac{1}{Z_c + R_T}$$

where $R_T = R_{T1} + R_{T2} = 25\ \Omega$

Thus far, no approximations have been made Equation (B 6) holds even if the resistors are assumed to have complex impedance.

The value of V_B/V_A for $Z_c = 0\ \Omega$ is

$$K/R_T = 0{,}0333$$

corresponding to an attenuation of 29,6 dB

B.4 Calibration with reference resistor $R_n = 25\ \Omega$

As K does not depend on Z_c, application of formula (B 6) yields:

for a reference resistor R_n inserted in the π-network

$$\frac{V_{Bn}}{V_{An}} = \frac{K}{R_n + R_T} \qquad \text{(B.7)}$$

for a crystal with impedance Z_c inserted in the π-network

$$\frac{V_{Bc}}{V_{Ac}} = \frac{K}{Z_c + R_T} \qquad \text{(B.8)}$$

By dividing (B.7) by (B.8) and solving the equation for Z_c one obtains

$$Z_c = \frac{V_{Bn}}{V_{An}} \times \frac{V_{Ac}}{V_{Bc}} (R_n + R_T) - R_T \qquad \text{(B 9)}$$

At the resonance frequency f_r the crystal impedance Z_c is equal to the resonance resistance R_r, which gives

$$R_r = \left[\frac{V_{Bn}}{V_{An}} \times \frac{V_{Ac}}{V_{Bc}} \left(\frac{R_n}{R_T} + 1 \right) - 1 \right] R_T \qquad \text{(B 10)}$$

For $R_n = R_T = 25\ \Omega$ the above equation results in the formula used in 6.2 2 7.

B.5 Error analysis for the resonance resistance R_r

The influence of measuring deviations on the resonance resistance R_r can be derived from equation (B 10).

$$\Delta R_r = \frac{\partial R_r}{\partial V_{Bn}} \Delta V_{Bn} + \ldots + \frac{\partial R_r}{\partial V_{Ac}} \Delta V_{Ac} + \frac{\partial R_r}{\partial R_n} \Delta R_n + \frac{\partial R_r}{\partial R_T} \Delta R_T$$

$$= \left(\frac{\Delta V_{Bn}}{V_{Bn}} - \frac{\Delta V_{An}}{V_{An}} + \frac{\Delta V_{Ac}}{V_{Ac}} - \frac{\Delta V_{Bc}}{V_{Bc}} \right) \frac{V_{Bn}}{V_{An}} \times \frac{V_{Ac}}{V_{Bc}} (R_n + R_T) + \tag{B.11}$$

$$+ \frac{V_{Bn}}{V_{An}} \times \frac{V_{Ac}}{V_{Bc}} \Delta R_n + \left(\frac{V_{Bn}}{V_{An}} \times \frac{V_{Ac}}{V_{Bc}} - 1 \right) \Delta R_T$$

where

ΔV_{An}, ΔV_{Bn} are the measuring deviations of r f voltage in the channels A and B with reference resistor R_n inserted in the π-network;

ΔV_{Ac}, ΔV_{Bc} are the measuring deviations of r f voltage in the channels A and B with a crystal inserted in the π-network,

ΔR_n is the deviation of the reference resistor from its nominal value,

ΔR_T is the deviation of the termination resistance of the π-network (as seen by the crystal) from its nominal value.

If R_n is equal to the crystal resistance, then $V_{An} \approx V_{Ac}$ and $V_{Bn} \approx V_{Bc}$ and the last term of formula (B 11), which contains the errors of the π-network, will vanish

Formula (B.11) corresponds to the one in clause A 4 of appendix A

B.6 Crystal current and drive level in the π-network

According to figure B.1 the crystal current at resonance is given by

$$I_c = \frac{\left(V_{Ac}'' - V_{Bc}' \right)}{R_r} \tag{B 12}$$

From equation (B.1) one obtains

$$V_{Bc}' = \frac{1}{k_\pi} V_{Bc}$$

Combining equations (B 1) and (B.2) yields

$$V_{Ac}'' = \frac{R_r + R_{T2}}{R_{T2}} \times \frac{1}{k_\pi} V_{Bc}$$

Substitution into equation (B.12) gives

$$I_c = \frac{1}{k_\pi R_{T2}} V_{Bc} = \frac{V_{Bc}}{4{,}56\ \Omega} \qquad (B.13)$$

Crystal drive level in the π-network can then be calculated from

$$P_c = R_r \times I_c^2 \qquad (B.14)$$

For the measurement set-up in this standard, equations (B.13) and (B.14) are used with $R_n = 25\ \Omega$ instead of R_r, i.e.

$$I_n = \frac{1}{k_\pi R_{T2}} V_{Bn} = \frac{V_{Bn}}{4{,}56\ \Omega}$$

and

$$P_n = R_n \times I_n^2$$

B.7 Phase slope of the crystal inserted in the π-network

If the crystal is approximated by its motional branch, its impedance can be written as

$$Z_c \approx R_1 + j X_1$$

where $X_1 = \omega L_1 - \dfrac{1}{\omega C_1}$

Substituting this relation into equation (B.6) yields

$$\frac{V_{Bc}}{V_{Ac}} = K \frac{1}{Z_c + R_T} = K \frac{1}{R_1 + R_T + j\ X_1}$$

As K is real, the phase of V_{Bc} / V_{Ac} is given by

$$\varphi = \arctan\left(\frac{\operatorname{Im}\left(\dfrac{V_{Bc}}{V_{Ac}}\right)}{\operatorname{Re}\left(\dfrac{V_{Bc}}{V_{Ac}}\right)} \right) = -\arctan\left(\frac{X_1}{R_1 + R_T} \right)$$

Near resonance the narrow band approximation (see IEC 61080*)

$$Z_c \approx R_1 + j\, 2\, \omega_s L_1 \left(\frac{\Delta\omega}{\omega_s} \right)$$

where $\omega_s = \frac{1}{\sqrt{L_1 C_1}}$ and $\Delta\omega = \omega - \omega_s$, can be used

The phase of V_{Bc}/V_{Ac} then can be expressed as

$$\varphi = -\arctan \left(\frac{2\, \omega_s L_1}{R_1 + R_T} \left(\frac{\Delta\omega}{\omega_s} \right) \right)$$

For $\Delta\omega \approx 0$ the arctan can be replaced by its argument Thus, the important relation is finally obtained.

$$\varphi \approx -2\, Q_{eff} \frac{\Delta f}{f_s} \qquad \text{(B.15)}$$

where

$$Q_{eff} = \frac{\omega_s L_1}{R_1 + R_T} \qquad \text{(B.16)}$$

is the quality factor of the crystal loaded by the termination impedance of the π-network

The formula for Q_{eff} given in appendix A of this standard is incorrect and is therefore to be replaced by formula (B.16).

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[*] IEC 61080 1991, *Guide to the measurement of equivalent electrical parameters of quartz crystal units*

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